Spin-alignment of Moving Heavy Quarkonium from Spin Chromomagnetic Coupling

Zhishun Chen

Date: 2024/12/10

Under the guidance of Shu Lin

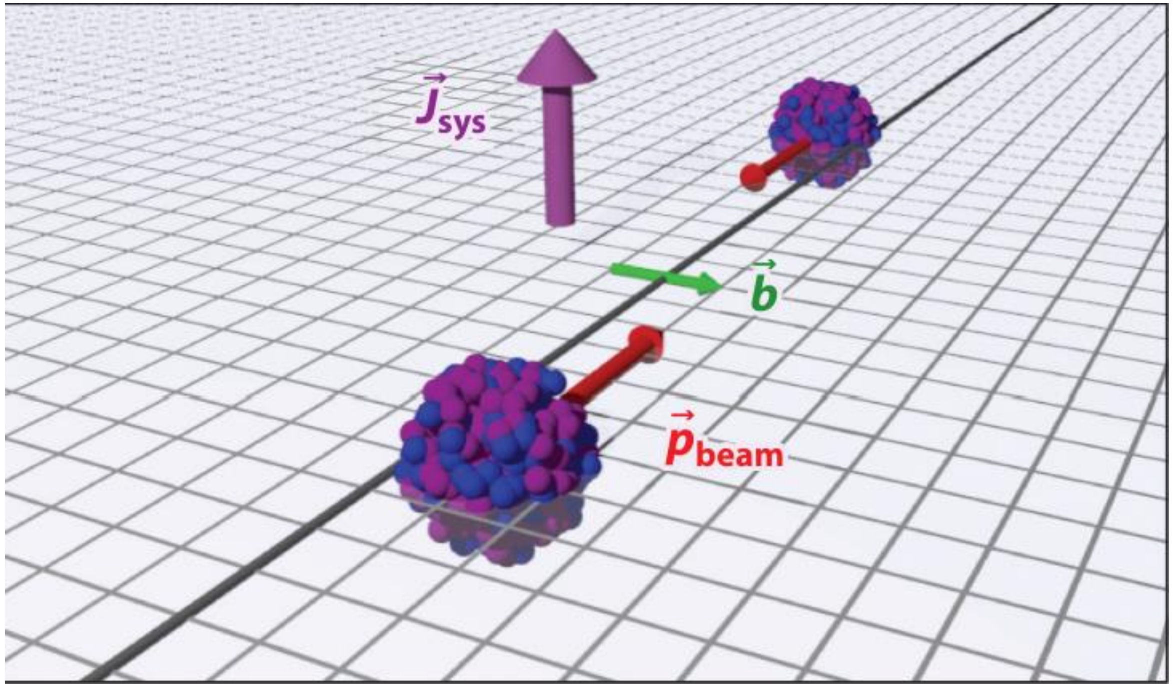


Figure from F. Becattini-Michael A. Lisa, AR 2020

- First idea in spin alignment

  Liang, Wang PRL 2005, PLB 2005

- Hyperon polarization can be nicely describe by hydrodynamic and transport-based calculations

- vector meson polarization still not clear...

  Vector meson field fluctuation
  Glasma field fluctuation
  Vorticity field
  EM field
  Fragmentation

01 Background

Spin density matrix

$$\rho = \sum_i P_i \, |\psi_i\rangle\langle\psi_i|$$

① $$\rho = \rho^\dagger$$

② $$\mathrm{Tr}\rho = \sum_i P_i = 1$$

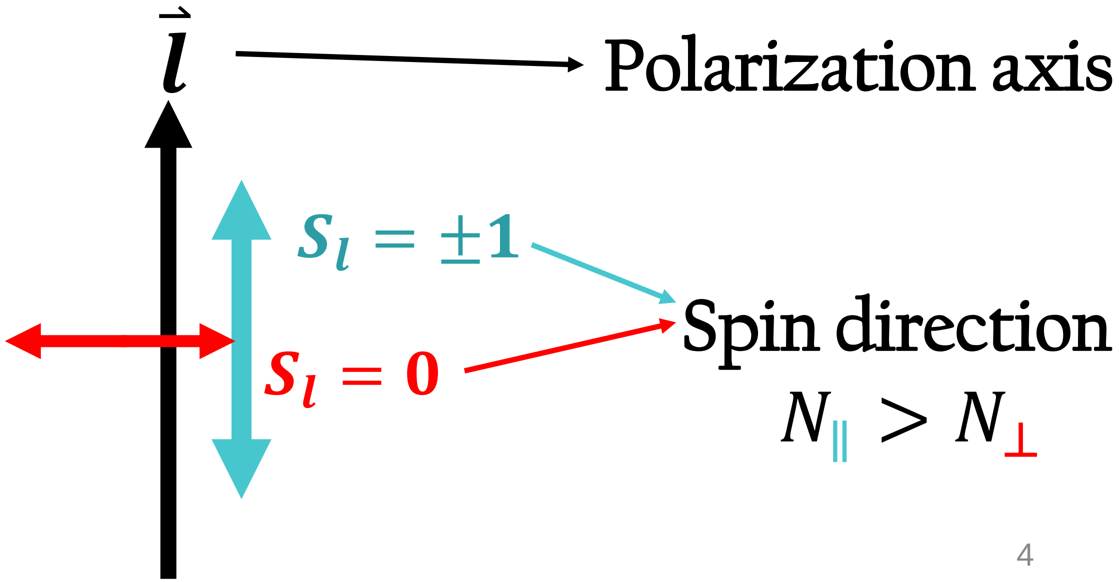
③ $$\langle\varphi|\rho|\varphi\rangle \geq 0$$

no polarization case:

$$\rho = \frac{1}{2S+1}\begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix}$$

$$\rho \overset{S=1}{\Longrightarrow} \frac{1}{3}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

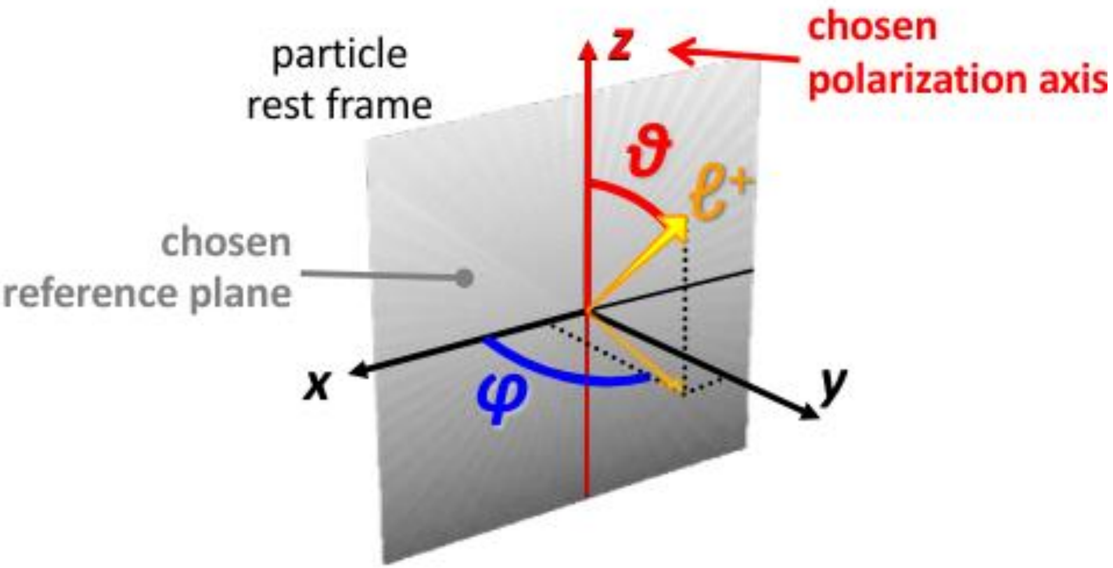
If $\rho_{00} < 1/3$

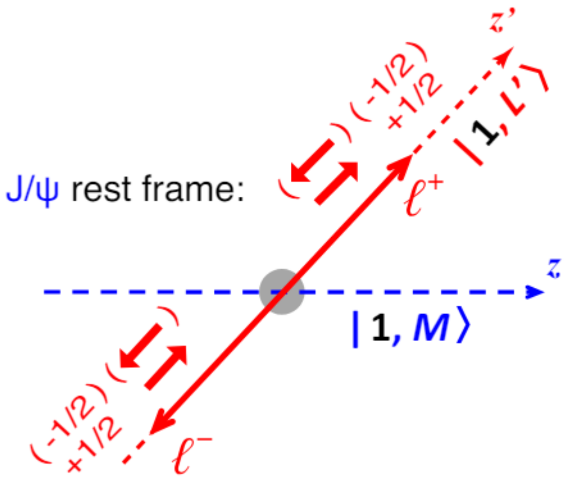


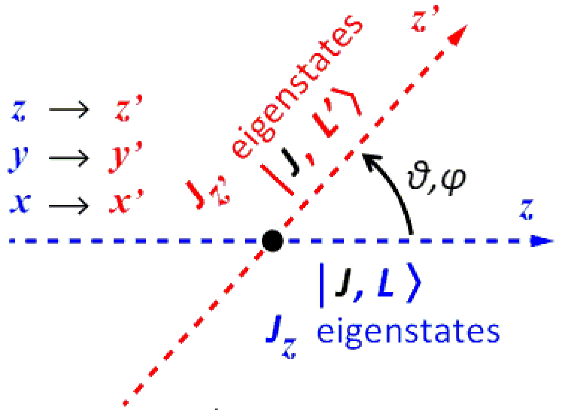
01

Background

The measurement of spin alignment in experiment







$$|J/\psi\rangle = \sum_{M=0,\pm1} a_M \, |J/\psi; 1, M\rangle_z$$

$$|J, L'\rangle = \sum_{L=-J}^{+J} \mathcal{D}^{J}_{L L'}(\vartheta,\varphi)\, |J, L\rangle$$

$$W(\vartheta) = \frac{1 + \lambda_\vartheta \cos^2\vartheta}{3 + \lambda_\vartheta}$$

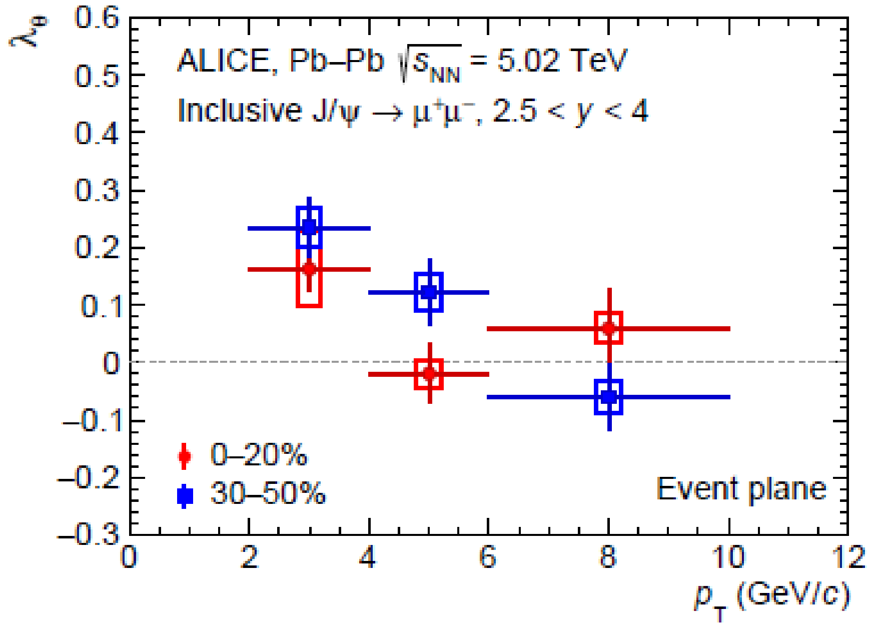
$$\lambda_\vartheta = \frac{1 - 3|a_0|^2}{1 + |a_0|^2}, \text{actually } |a_0|^2 = \rho_{00}$$

Background

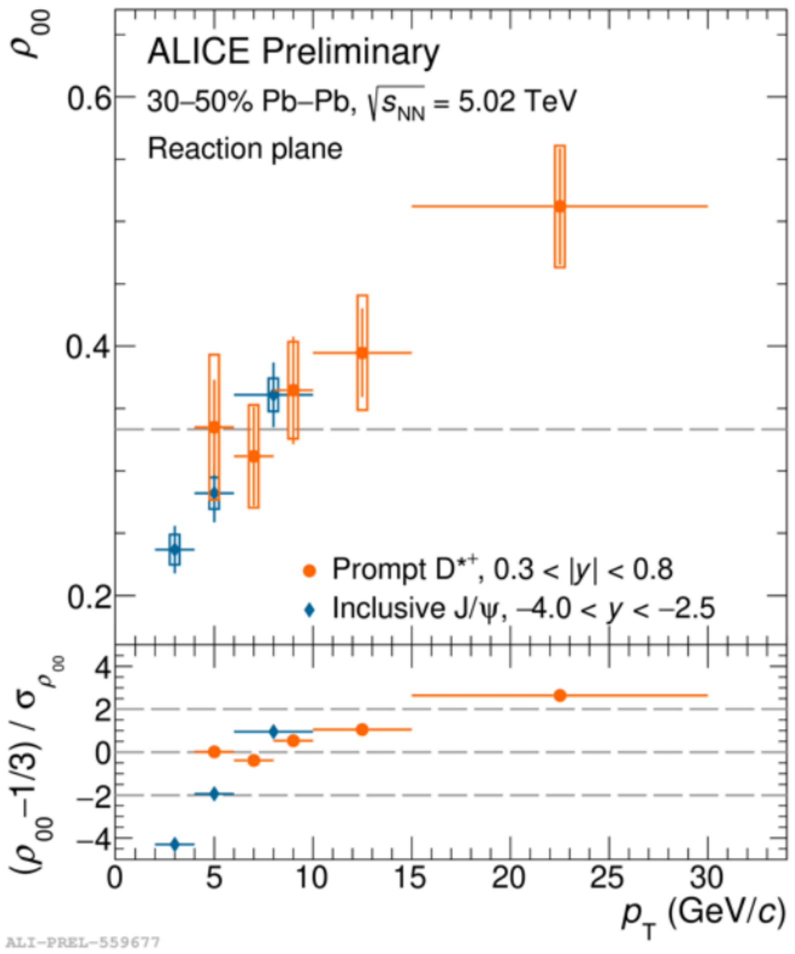
Recent measurement about spin alignment

The parameters of polar angle distribution are measured.

$$\lambda_\vartheta \propto (1 - 3\rho_{00})/(1 + \rho_{00})$$



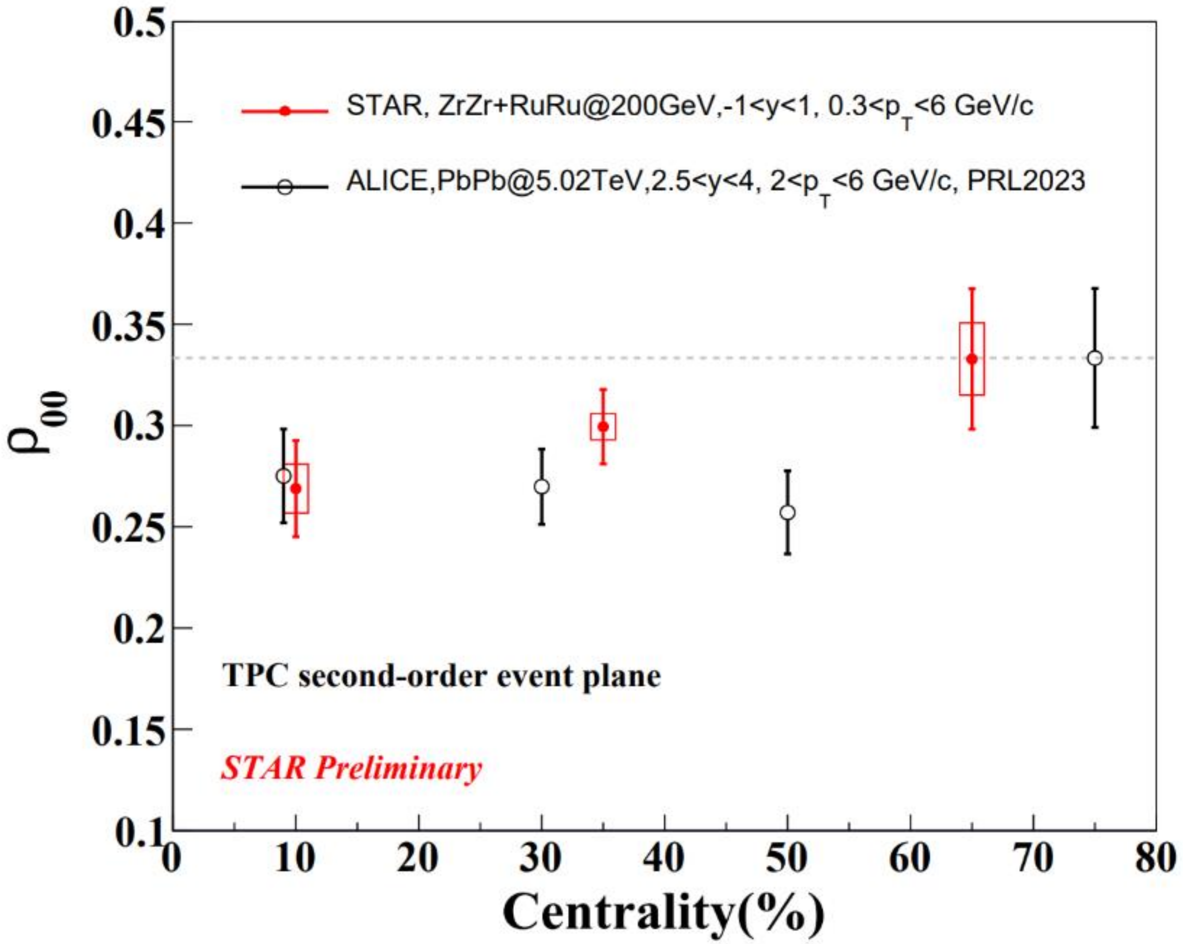
ALICE, PRL 2023



Talk by Zebo Tang

$$\rho_{00} < 1/3$$

RHIC vs LHC



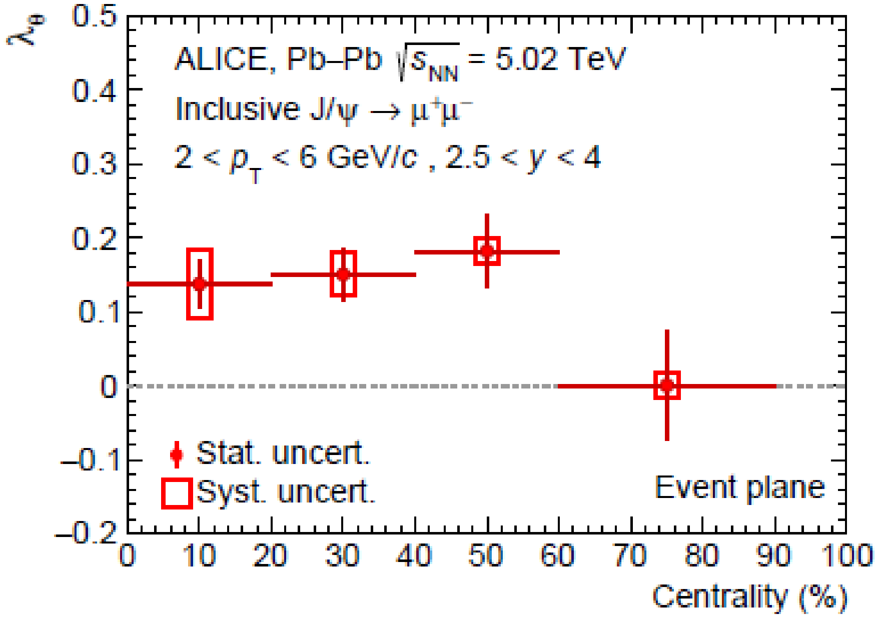
Talk by Dandan Shen

The ρ_{00} at RHIC energy has the same sign with that at LHC energy.

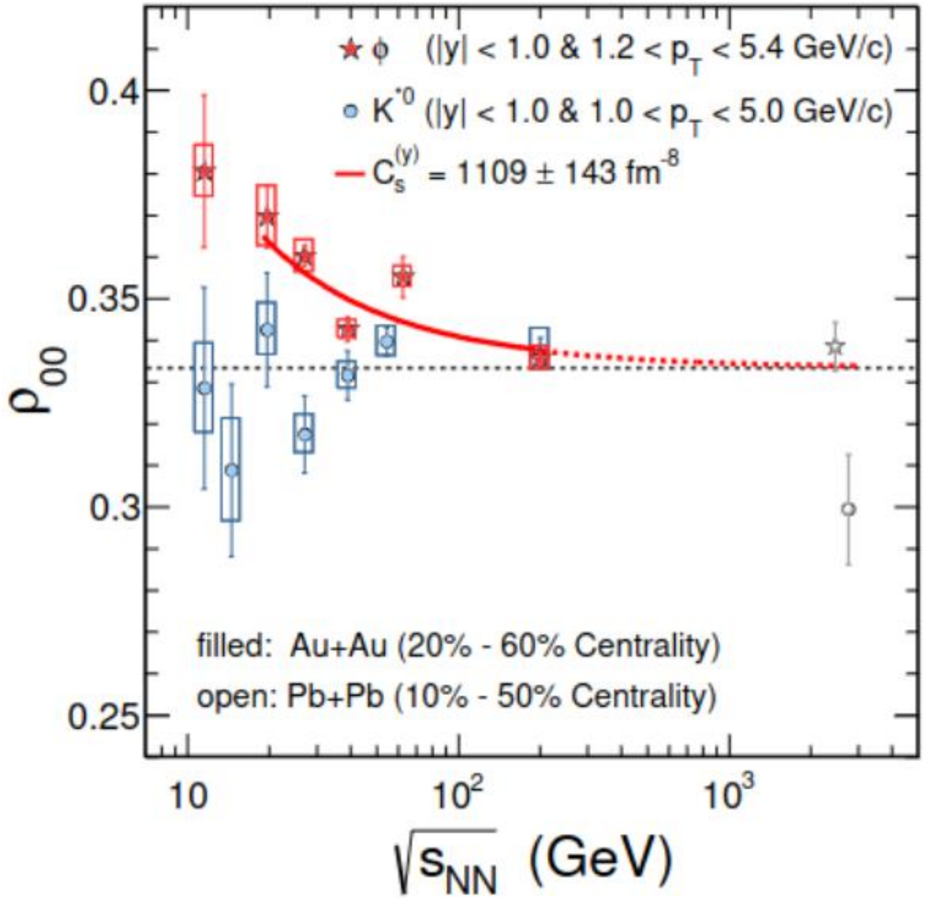
Background

Other measurement about spin alignment

J/ψ vs ϕ

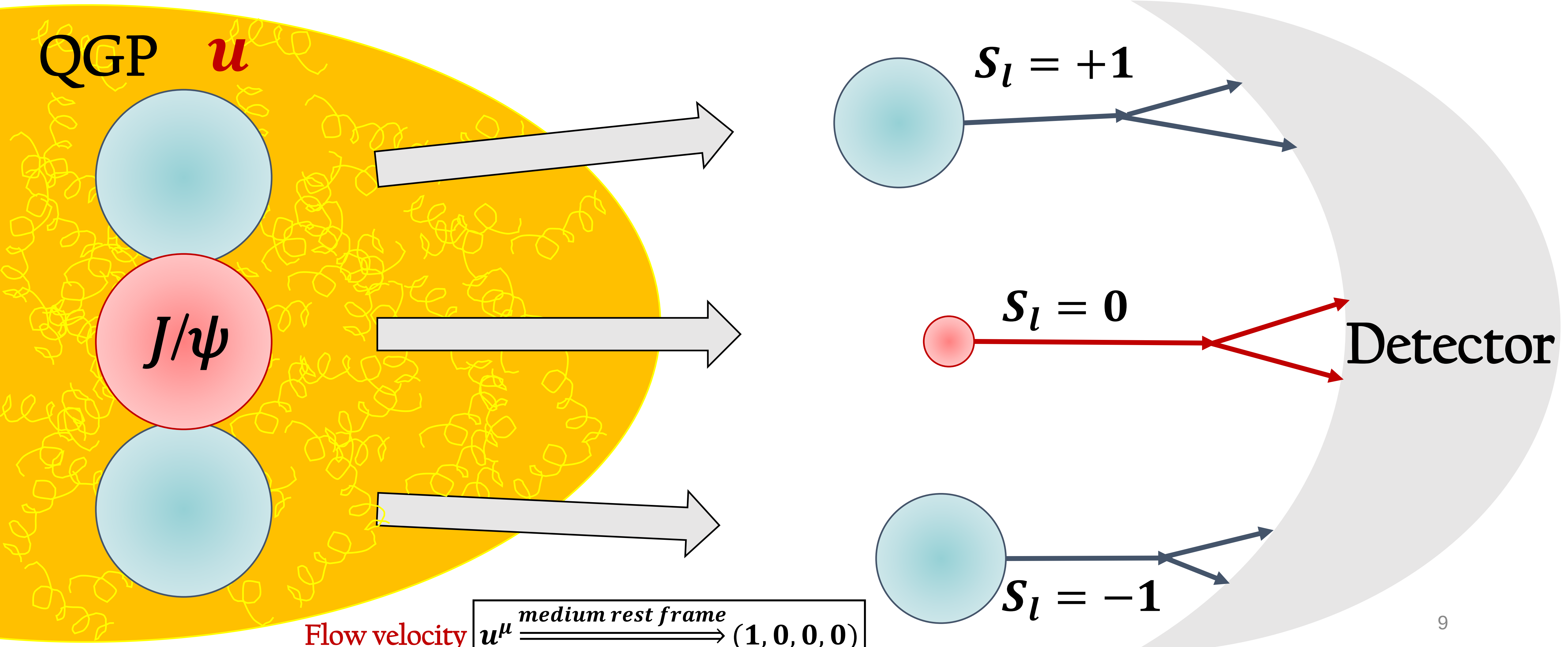


$\rho_{00} < 1/3$



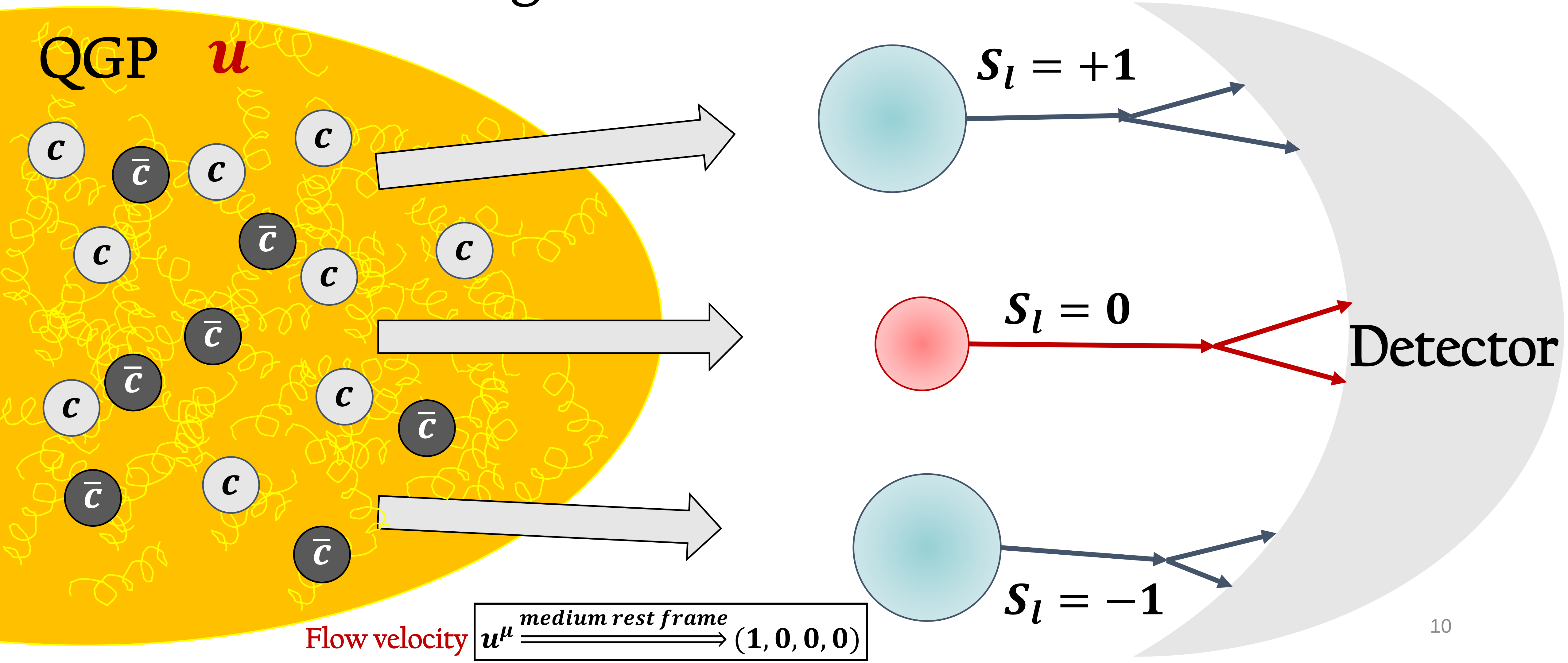
Opposite to ϕ

Dissociation dominant case



Flow velocity $u^\mu \xrightarrow{medium\ rest\ frame} (1,0,0,0)$

Regeneration dominant case



Flow velocity $u^\mu \xrightarrow{medium\ rest\ frame} (1, 0, 0, 0)$

Dissociation dominant

$\rho_{00} < 1/3$ requires damping rate

$$\Gamma_0(u, l) > \bar{\Gamma}(u)$$

Regeneration dominant

$\rho_{00} < 1/3$ requires gain rate

$$D_0(u, l) < \bar{D}(u)$$

1. Evaluate the spin-dependent loss term and gain term.
2. Solve the transport equation of J/ψ in different spin state.

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1. Evaluate the spin-dependent loss term and gain term.
2. Solve the transport equation of J/ψ in different spin state.

$$H_{Q\bar{Q}} = H + H_I$$

$$H = \frac{\vec{p}^2}{m_Q} + V_s(|\vec{r}|) + \sum_a \frac{\lambda_a}{2}\frac{\bar{\lambda}_a}{2} V_o(|\vec{r}|)$$

$$H_I = Q^a A_0^a(t,\vec{0}) - \vec{d}^a \cdot \vec{E}^a(t,\vec{0}) - \vec{\mu}^a \cdot \vec{B}^a(t,\vec{0}) + \ldots$$

Yan, PRD 1980;
Kuang-Yan, PRD 1981

$Q\bar{Q}$ potential arise from gluon exchange with color singlet & color octet

Expanding in relative coordinate and mass, the leading order potential in pNRQCD framework

$$V_s^{(0)} = -C_F \frac{\alpha_s}{r} \qquad V_o^{(0)} = \frac{1}{2N_c}\frac{\alpha_s}{r}$$

Brambilla et all,
Nucl. Phys. B 2000

$$H_{Q\bar{Q}} = H + H_I$$

Yan, PRD 1980;
Kuang-Yan, PRD 1981

$$H = \frac{\vec{p}^2}{m_Q} + V_s(|\vec{r}|) + \sum_a \frac{\lambda_a}{2}\frac{\bar{\lambda}_a}{2} V_o(|\vec{r}|)$$

J/ψ rest frame

$$H_I = Q^a A_0^a(t,\vec{0}) - \vec{d}^a \cdot \vec{E}^a(t,\vec{0}) - \vec{\mu}^a \cdot \vec{B}^a(t,\vec{0}) + \ldots$$

Spin-independent

$$Q^a = g_s\left(\frac{\lambda_a}{2} + \frac{\bar{\lambda}_a}{2}\right)$$

Chromo-monopole

$$\vec{d}^a = \frac{g_s}{2}\vec{r}\left(\frac{\lambda_a}{2} - \frac{\bar{\lambda}_a}{2}\right)$$

Chromoelectric dipole

Spin-dependent

$$\vec{\mu}^a = \frac{g_s}{2m_Q}\left(\frac{\lambda^a}{2} - \frac{\bar{\lambda}^a}{2}\right)\left(\frac{\vec{\sigma}}{2} - \frac{\vec{\sigma}'}{2}\right)$$

Chromomagnetic dipole
Suppressed by heavy quark's mass

02

Physical pictures

Different possible case for spin alignment

Dissociation dominant

$\rho_{00} < 1/3$ requires damping rate

$$\Gamma_0(u, l) > \bar{\Gamma}(u)$$

Regeneration dominant

$\rho_{00} < 1/3$ requires gain rate

$$D_0(u, l) < \bar{D}(u)$$

1. Evaluate the spin-dependent loss term and gain term.
2. Solve the transport equation of J/ψ in different spin state.

Dissociation dominant case

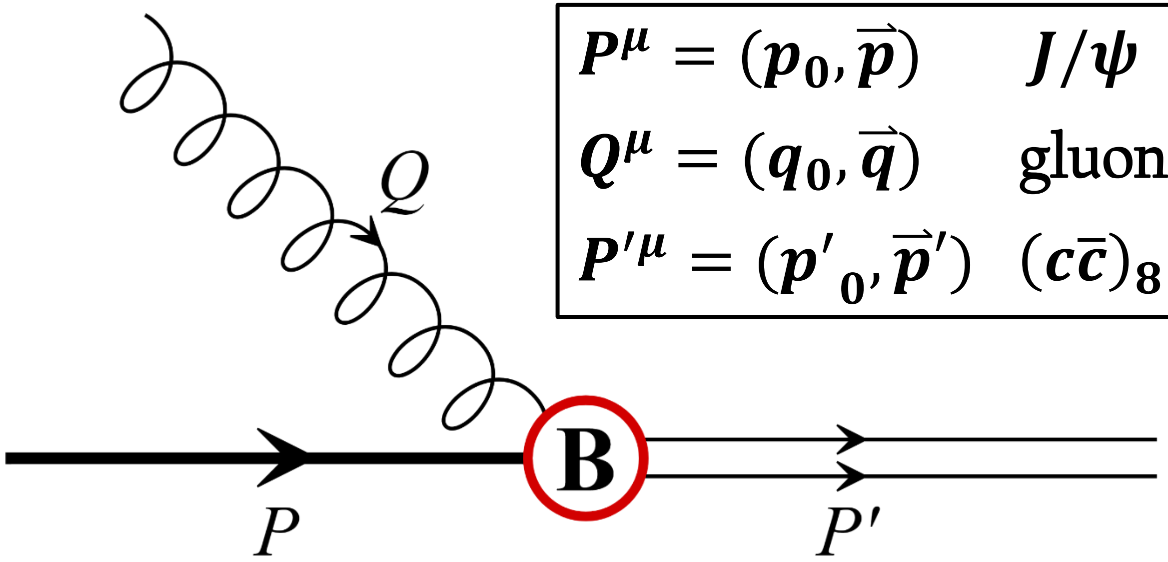
$P^\mu \partial_\mu f^i = -C^i f^i + \cancel{D^i}$ $\quad i = 0, \pm$ represent different spin state

Spin density matrix 00 component: $\rho_{00} = \dfrac{f^0}{\sum_i f^i}$

1. Only J/ψ evolution in the system
2. All J/ψ are produced at t=z=0 $\delta(\eta - Y)$ Zhu-Zhuang-Xu, PLB 2005
3. Divide into two parts: $C^i = C^E(u, P) + C^{B,i}(u, P, l)$

Gluon-dissociation (LO) process

Transition probability of Chromomagnetic dipole



$P^{\mu} = (p_0, \vec{p})$	J/ψ
$Q^{\mu} = (q_0, \vec{q})$	gluon
$P'^{\mu} = ({p'}_0, \vec{p}')$	$(c\bar{c})_8$

Spin average result — Chen-He, PRC 2017

Binding energy

$$\bar{\sigma}_{LO,B}(q_0) = \frac{2^3}{3} g_s^2 \frac{\epsilon_B^{5/2}}{m_Q^2} \frac{(q_0 - \epsilon_B)^{1/2}}{q_0^3}$$

LO result is suppressed by ϵ_B

$\epsilon_B \to 0\,, \bar{\sigma}_{LO,B} \to 0$

Spin Chromomagnetic coupling

$$\mathcal{M}_B \propto \frac{1}{2} \langle (c\bar{c})_8 | (\vec{\sigma} - \vec{\sigma}') \cdot \vec{B}^a | J/\psi \rangle$$

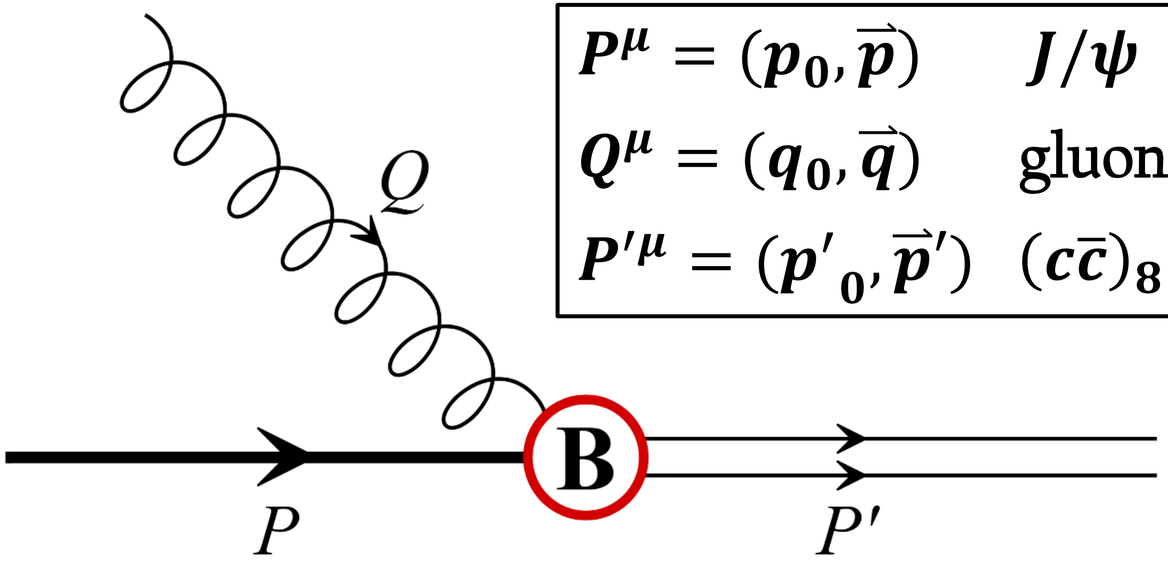
Choose $\vec{l}$ as quantization axis in J/ψ rest frame

$\vec{l}$

$$\bar{\sigma}_{LO,B} \propto |\mathcal{M}_B|^2_{spin\ average}$$

Gluon-dissociation (LO) process

Transition probability of Chromomagnetic dipole



$P^{\mu} = (p_0, \vec{p})$ J/ψ

$Q^{\mu} = (q_0, \vec{q})$ gluon

$P'^{\mu} = (p'_0, \vec{p}')$ $(c\bar{c})_8$

Different spin initial state

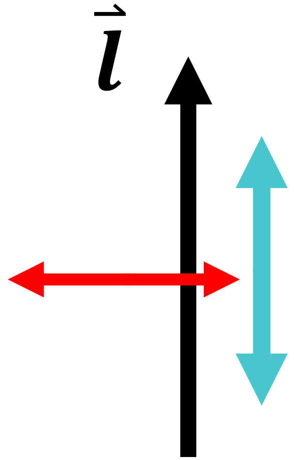
$$\left|(c\bar{c})_8\right\rangle = \frac{1}{\sqrt{2}}\left|\uparrow\downarrow - \downarrow\uparrow\right\rangle$$

$$|J/\psi\rangle = \begin{cases} |\uparrow\uparrow\rangle, & S_l = 1 \\ \frac{1}{\sqrt{2}}|\uparrow\downarrow + \downarrow\uparrow\rangle, & S_l = 0 \\ |\downarrow\downarrow\rangle, & S_l = -1 \end{cases}$$

Spin Chromomagnetic coupling

$$\mathcal{M}_B \propto \frac{1}{2}\left\langle (c\bar{c})_8 \middle| (\vec{\sigma} - \vec{\sigma}') \cdot \vec{B}^a \middle| J/\psi \right\rangle$$

Choose $\vec{l}$ as quantization axis in J/ψ rest frame



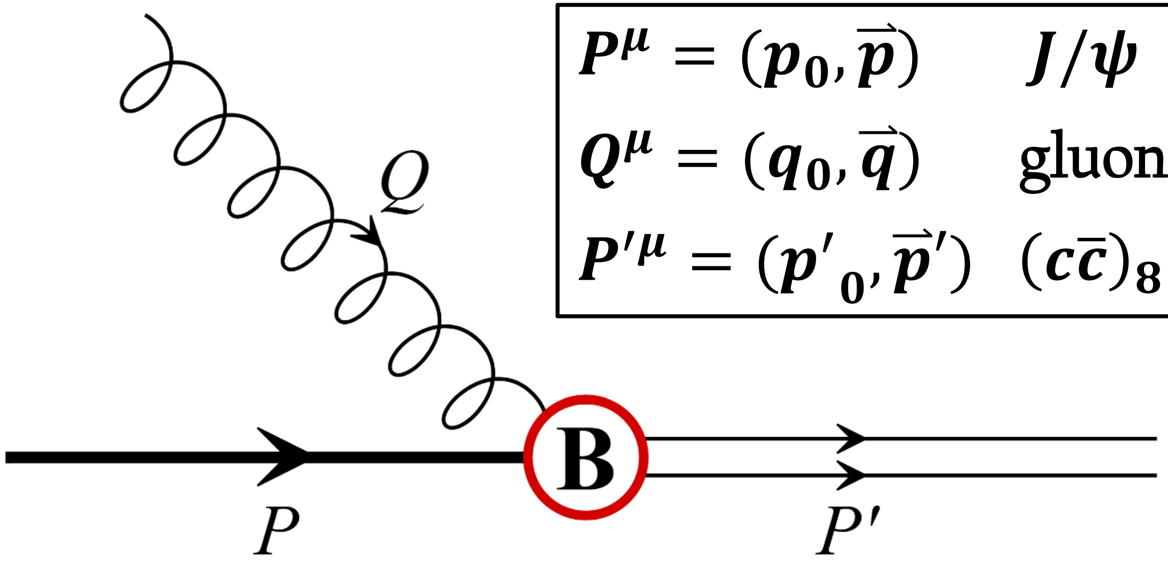
$$\left|\mathcal{M}_{S_l=\pm 1}\right|^2 \propto {B^a_{l\perp}}^2/2$$

$$\left|\mathcal{M}_{S_l=0}\right|^2 \propto {B^a_l}^2$$

03

Gluon-dissociation (LO) process

Transition probability of Chromomagnetic dipole



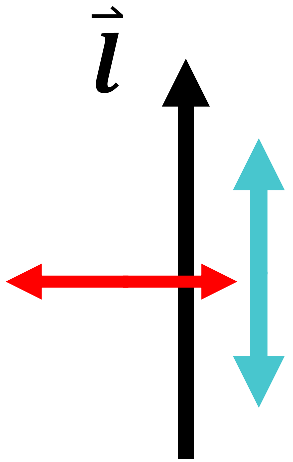
$P^\mu = (p_0, \vec{p})$	J/ψ
$Q^\mu = (q_0, \vec{q})$	gluon
$P'^\mu = (p'_0, \vec{p}')$	$(c\bar{c})_8$

Spin-dependent Dissociation coefficient proportional to $|\mathcal{M}_i|^2$

$$\left|\mathcal{M}_{S_l=0}\right|^2 \propto B_l^{a\,2} \quad \Longrightarrow$$

$$3\bar{C}_B = C_B^0 + C_B^+ + C_B^- \propto 2q^2$$

$$C_B^0 \propto q^i q^j (\delta_{ij} - l_i l_j)$$



$$\bar{C}_B = \frac{1}{2}\int \frac{d^3q}{(2\pi)^3 2q_0} \bar{\sigma}_{LO,B}(q_0)\, 4F_{g\psi}\, f_{MB}(Q\cdot u)$$

Maxwell-Boltzmann approximation

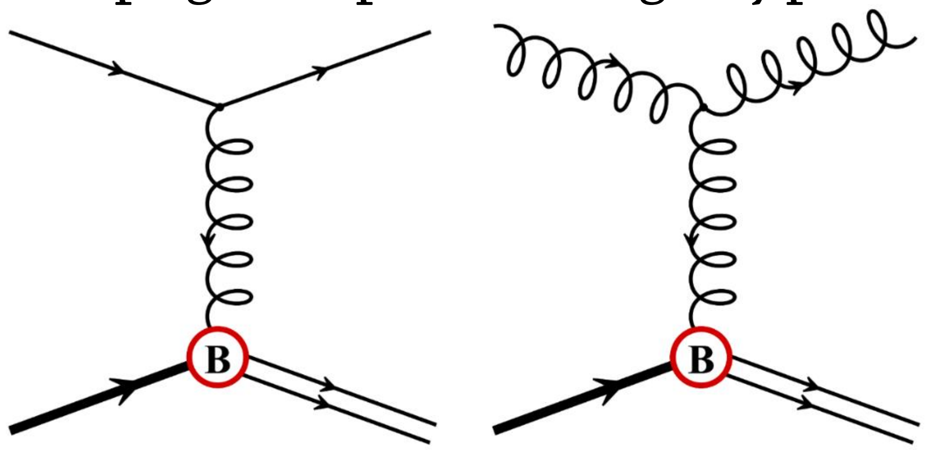
gluon in Medium

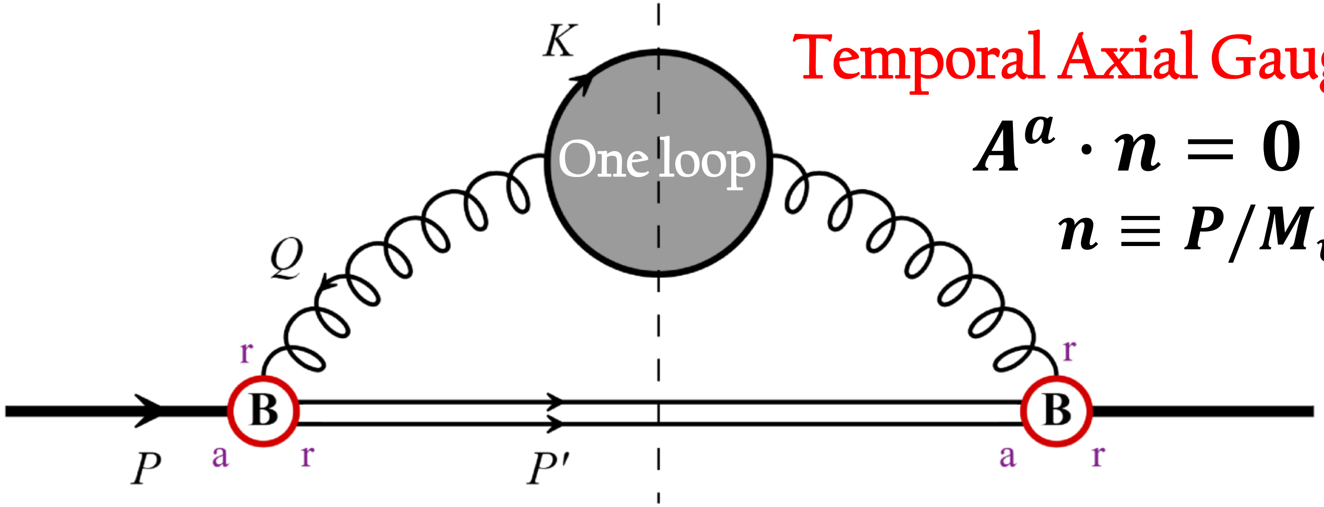
$$C_B^0 = \frac{1}{2}\int \frac{d^3q}{(2\pi)^3 2q_0} \frac{\bar{\sigma}_{LO,B}(q_0)}{2q^2/3} q^i q^j (\delta_{ij} - l_i l_j) 4F_{g\psi} f_{MB}(Q\cdot u)$$

Inelastic scattering (NLO) process

Gauge using

Damping corresponds to Imaginary part→



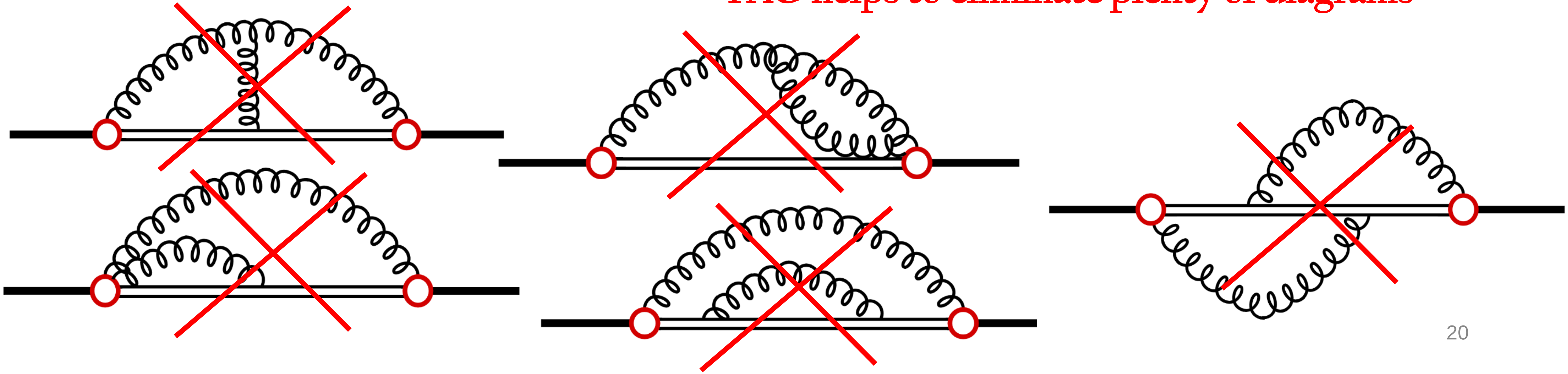


Temporal Axial Gauge

$$A^a \cdot n = 0$$

$$n \equiv P/M_\psi$$

TAG helps to eliminate plenty of diagrams

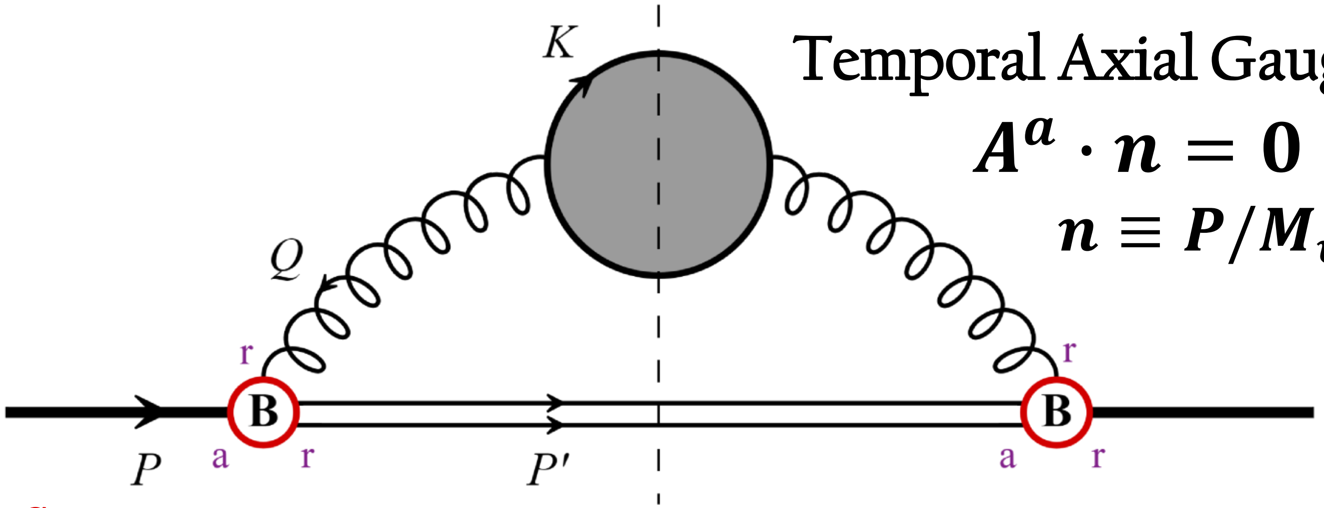


Inelastic scattering (NLO) process

Dissociation coefficient in v square expansion

Kinetic constraints:

1. Space-like gluon $Q^2 < 0$
2. Imaginary part $q < 2k \sim 2T$



Temporal Axial Gauge

$A^a \cdot n = 0$

$n \equiv P/M_\psi$

Parameterize the damping rate:

$B_i^a B_j^a$

$$\delta\Gamma_{ij}^{(2)} = \int_Q \left\langle 1S \left| \frac{g_s^2}{m_c^2}\frac{T_F}{N_c} \boxed{\varepsilon_{ikl} q_k \varepsilon_{jmn} q_m \delta D_{ln}^{rr(2)}} \pi\delta(q_0 - \epsilon_B - H_o^{(0)}) \right| 1S \right\rangle$$

$$\equiv c_1(T, \delta v^2)\,\delta_{ij} + c_2(T, \delta v^2)\,\hat{v}_i \hat{v}_j$$

Only anisotropic leads to spin-different damping

$$\left|\mathcal{M}_{S_l=0}\right|^2 \propto B_l^{a2} \Longrightarrow \bar{C}_B - C_B^0 = M_\psi c_2(T, \delta v^2)\left(\frac{1}{3} - (l \cdot \hat{v})^2\right)$$

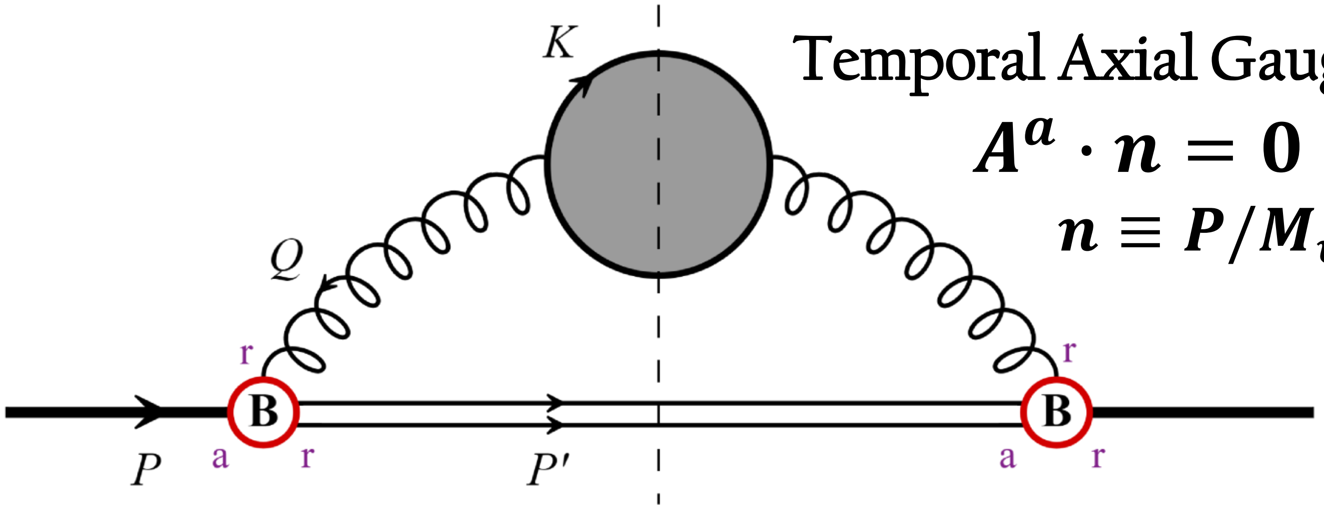
Inelastic scattering (NLO) process

Propagator in v square expansion

Assuming medium is moving slowly with respect to J/ψ :

$$u^{\mu} \equiv \left(\sqrt{1+(\vec{n}+\delta\vec{v})^2}, \vec{n}+\delta\vec{v}\right)$$

Calculate in J/ψ rest frame



Temporal Axial Gauge

$$A^a \cdot n = 0$$

$$n \equiv P/M_{\psi}$$

$$\delta\Pi_{gluon} = \Pi(u) - \Pi(n) \xrightarrow{\sim\mathcal{O}(\delta v^2)}$$

Vacuum Thermal

$$\delta D_{rr}^{(2)\mu\nu} = \left(2Re[D_{ra}(n)\,\delta\Pi\,D_{ra}(n)]^{\mu\nu}\left(\frac{1}{2} + f_{BE}(Q\cdot u)\right)\right)^{(2)}$$

$$\overline{C}_B - C_B^0 = M_{\psi}c_2(T, \delta v^2)\left(\frac{1}{3} - (l\cdot\hat{v})^2\right)$$

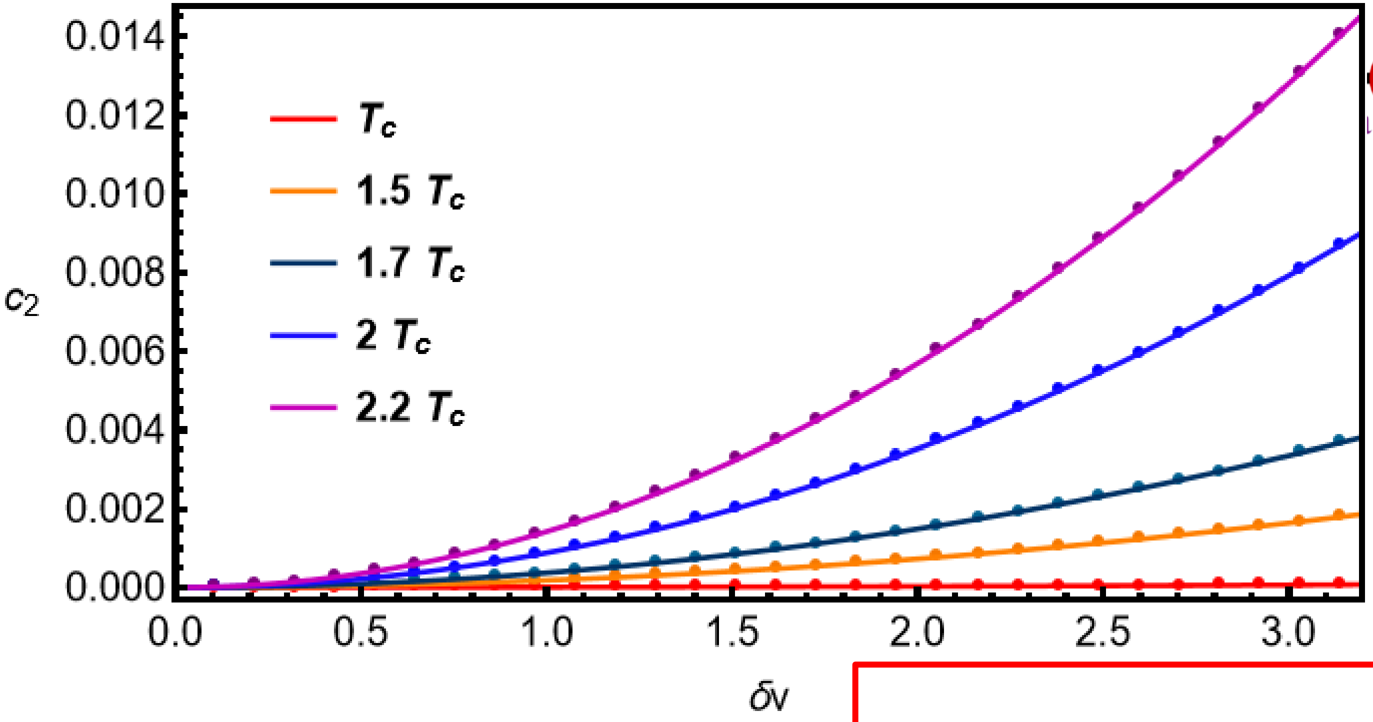
Inelastic scattering (NLO) process

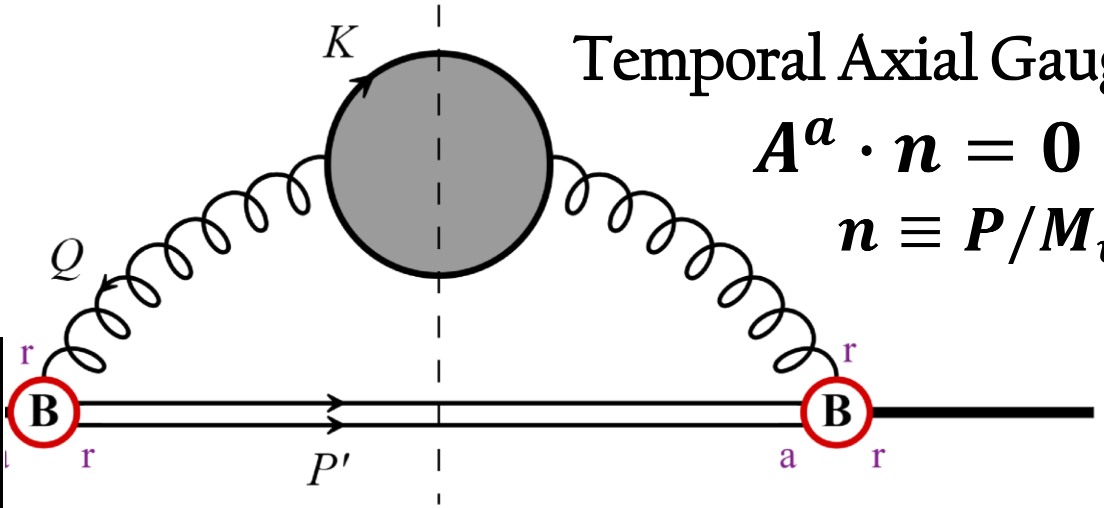
Result in HTL approximation

Hard Thermal Loop approximation

$$Q \ll T$$

c_2 with different temperature





Temporal Axial Gauge

$$A^a \cdot n = 0$$

$$n \equiv P/M_\psi$$

The background-independent coefficient c_2 is calculated

$$\overline{C}_B - C_B^0 = M_\psi c_2(T, \delta v^2)\left(\frac{1}{3} - (l \cdot \hat{v})^2\right)$$

Bjorken flow

$$P^{\mu}\partial_{\mu}f^{i} = -C^{i}f^{i} + D^{i}$$

$$\tilde{f}^{i}(\tau, Y, p_T) = exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C^E}{P\cdot u}\right] exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C_B^i}{P\cdot u}\right] \tilde{f}_0\,(\tau_0, Y, p_T)$$

Spin alignment

$$\rho_{00} - \frac{1}{3} \cong \frac{1}{3}\int_{\tau_0}^{\tau} d\tau' \frac{\overline{C}_B - C_B^0}{P\cdot u}$$

1. Only J/ψ evolution in the system
2. All J/ψ are produced at t=z=0 $\delta(\eta - Y)$ Zhu-Zhuang-Xu, PLB 2005
3. Divide into two parts: $C^i = C^{non}(u, P) + C^{spin,i}(u, P, l)$

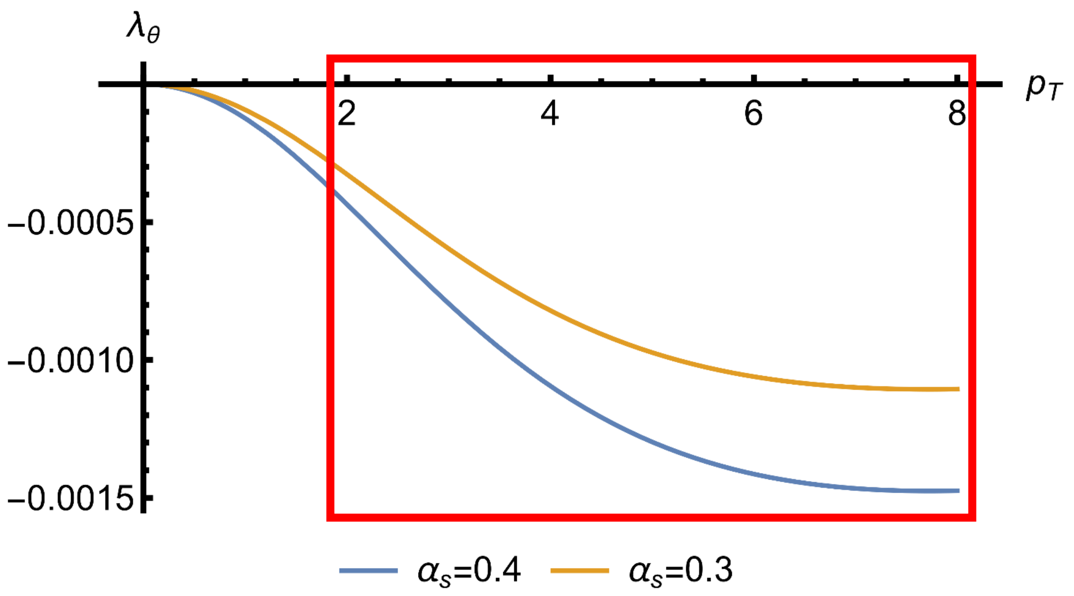
Bjorken flow

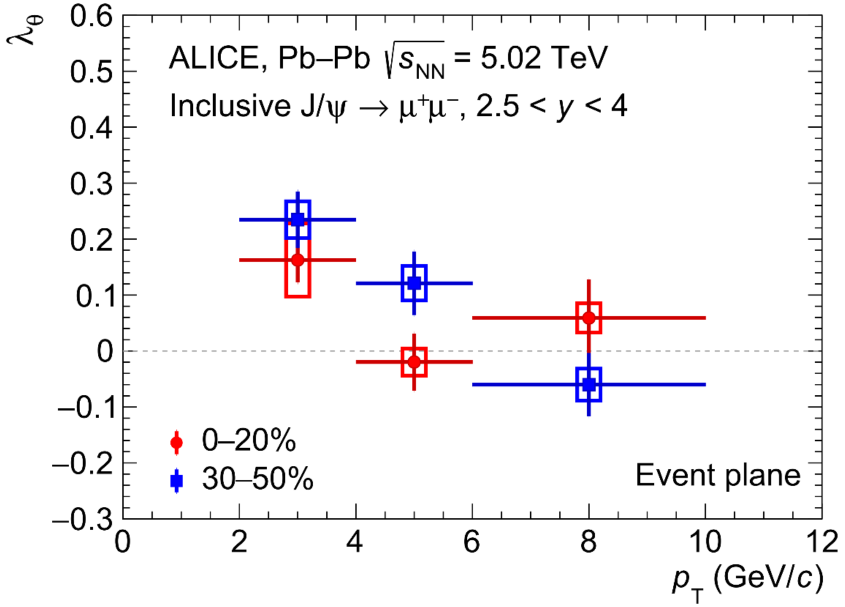
LO

Express in lab frame

$$\rho_{00} - \frac{1}{3} = \frac{1}{3} A \left[\frac{1}{3} + \frac{(-u\cdot l + n\cdot u\, n\cdot l)^2}{(n\cdot l)^2 + 1} - \frac{1}{3}(n\cdot u)^2 \right]$$

Parameter of integral



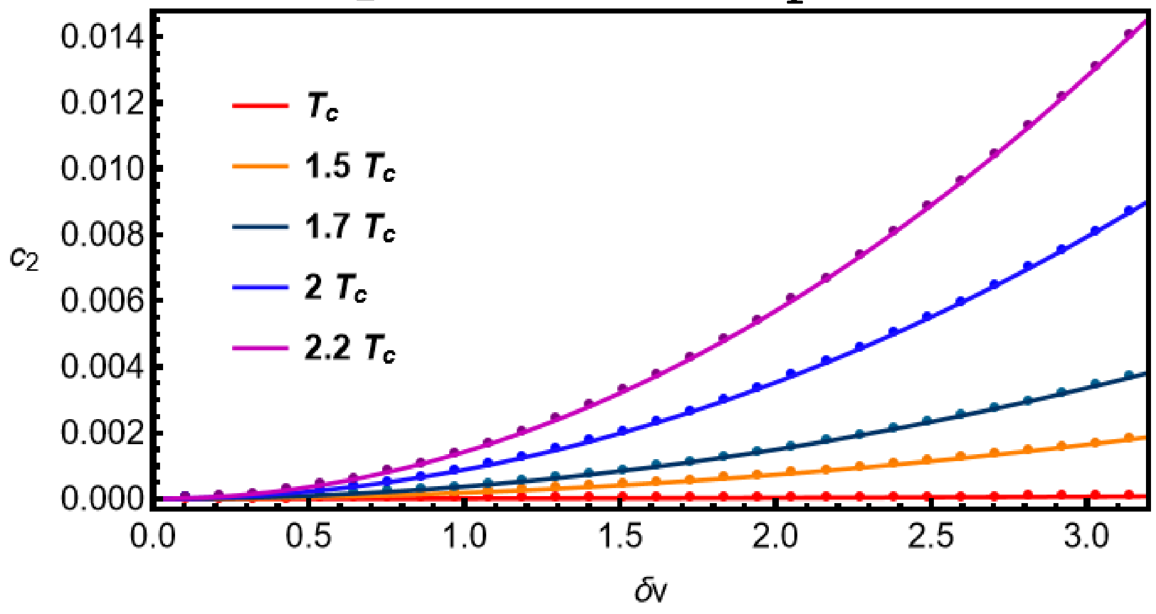


Dissociation in Bjorken flow only gives $\rho_{00} > 1/3$

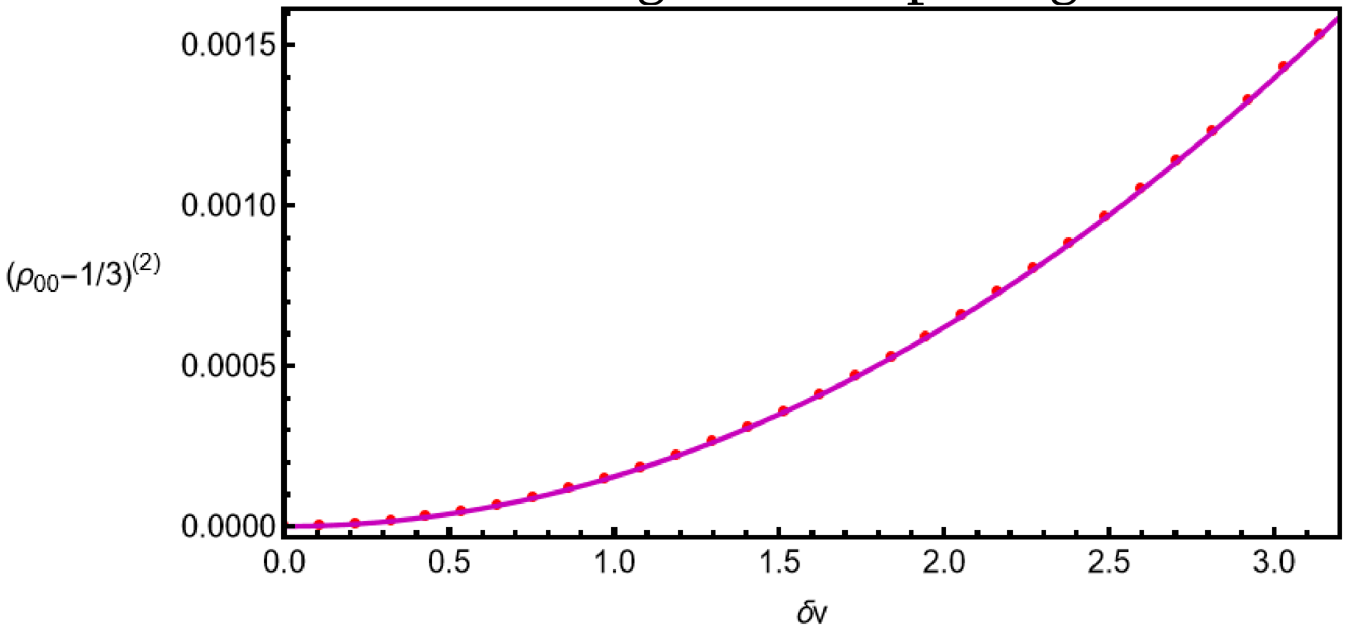
Bjorken flow

NLO

c_2 with different temperature



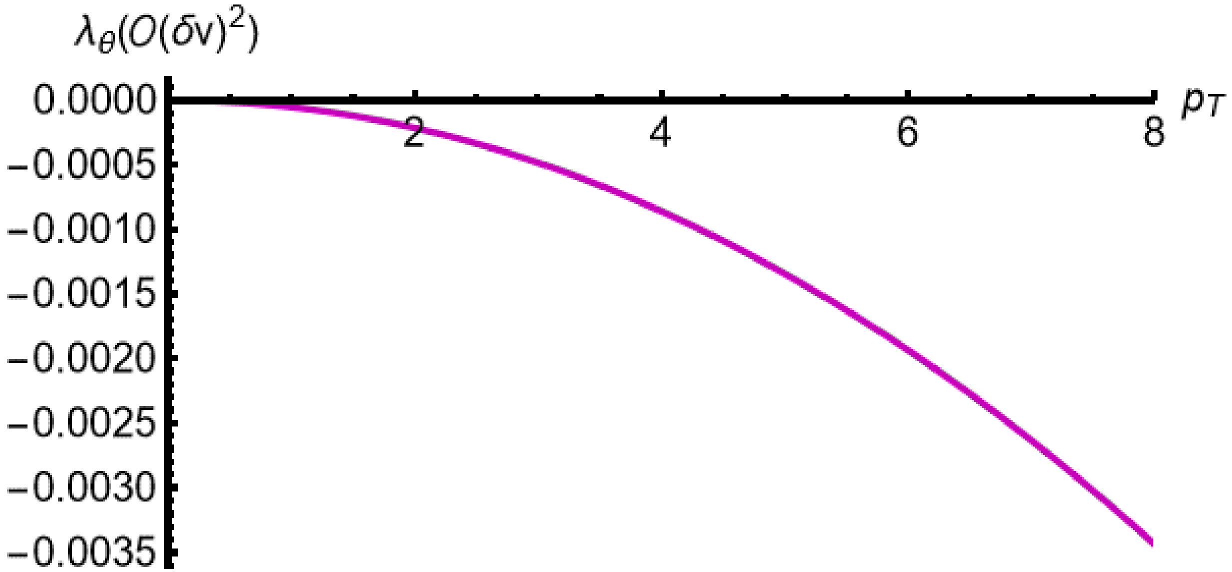
$l \cdot \hat{v}$ average result of spin-alignment

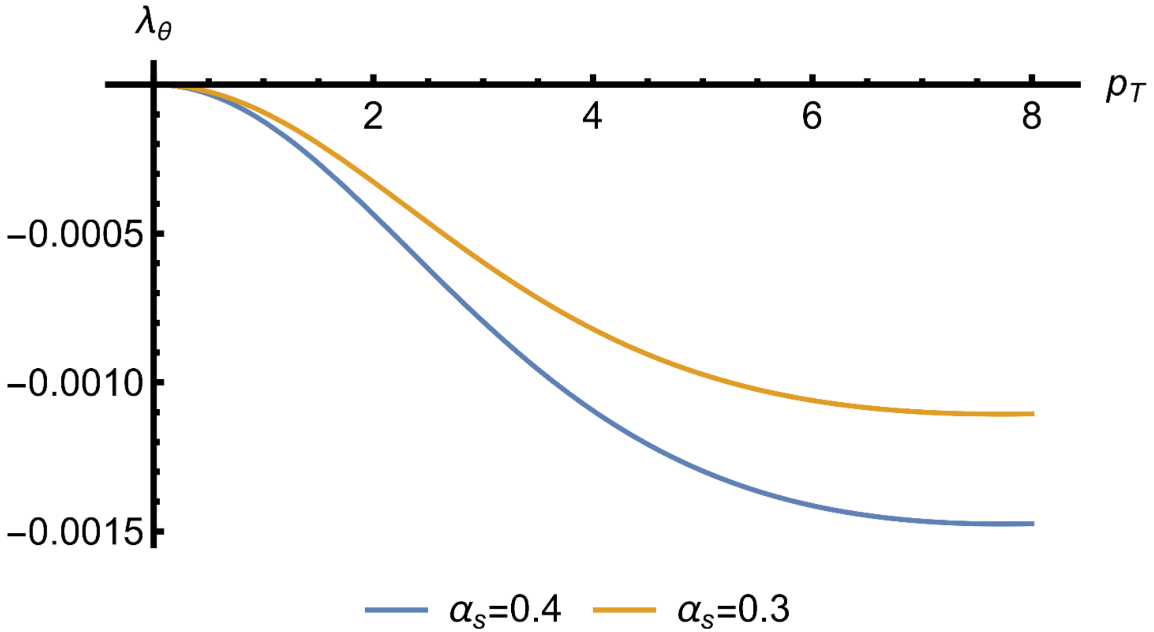


$$\left(\rho_{00}-\frac{1}{3}\right)^{(2)}=\frac{1}{3}\int_{\tau_0}^{\tau} d\tau'\; c_2\left(T,\delta v^2\right)\left(\frac{1}{3}-(l\cdot\hat{v})^2\right)$$

Bjorken flow

NLO vs LO

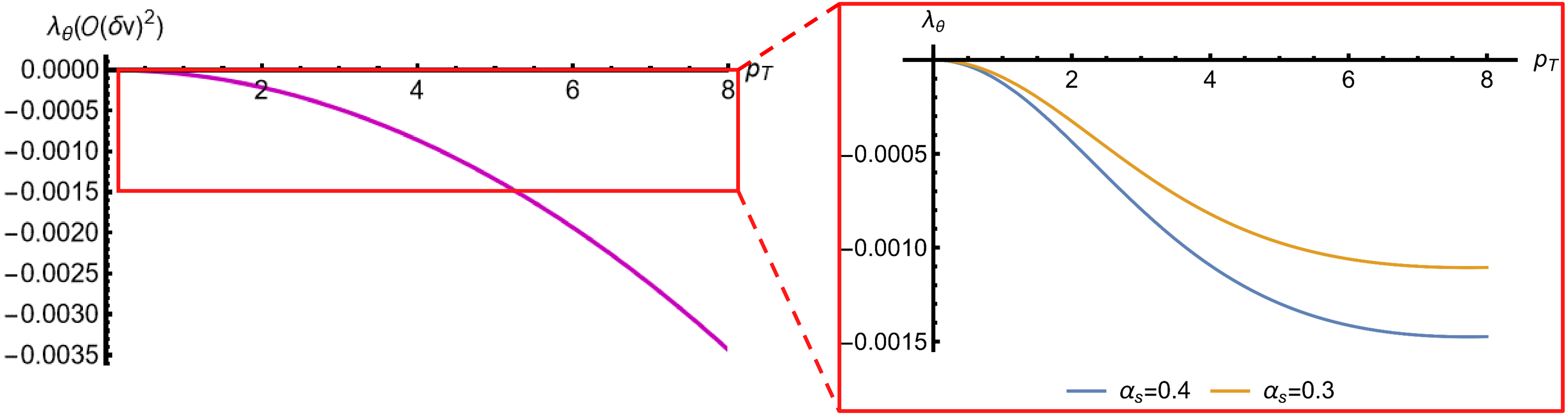




$$\left(\rho_{00}-\frac{1}{3}\right)^{(2)}=\frac{1}{3}\int_{\tau_0}^{\tau}d\tau'\,c_2(T,\delta v^2)\left(\frac{1}{3}-(l\cdot\hat{v})^2\right)$$

Bjorken flow

NLO vs LO

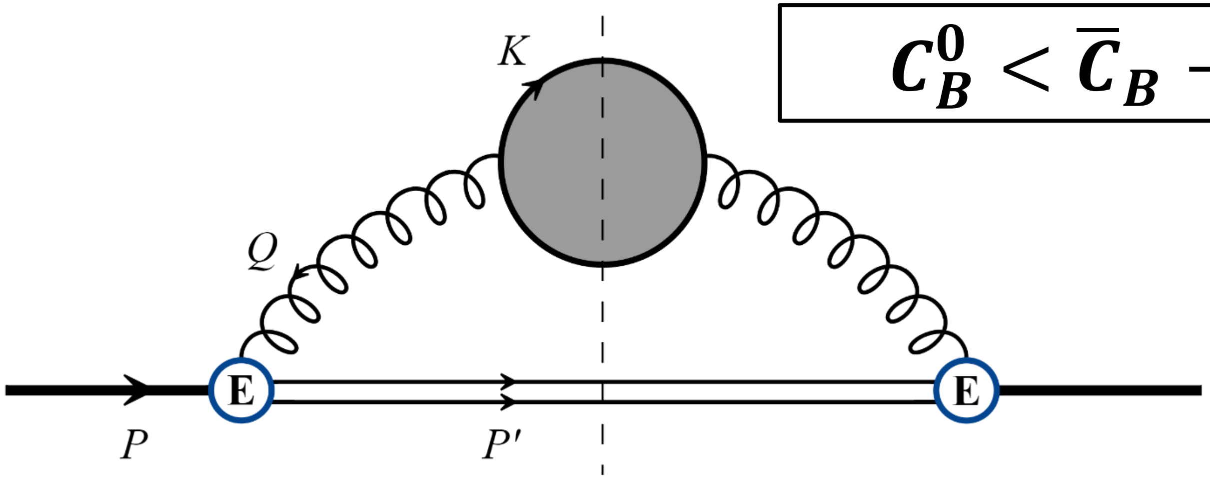


$$\left(\rho_{00}-\frac{1}{3}\right)^{(2)}=\frac{1}{3}\int_{\tau_0}^{\tau}d\tau'\;c_2\left(T,\delta v^2\right)\left(\frac{1}{3}-(l\cdot\hat{v})^2\right)$$

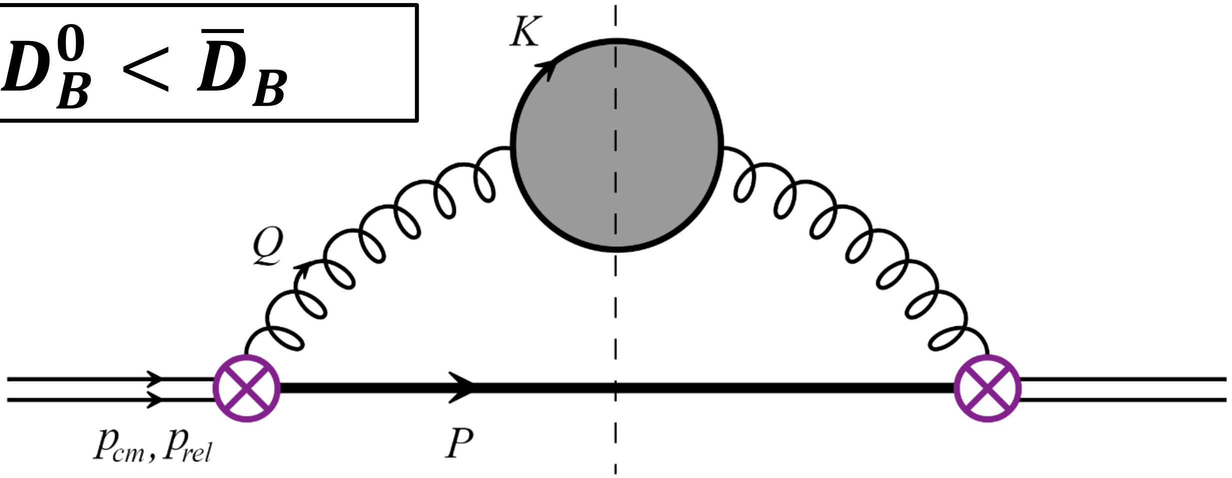
Regeneration Dominant case

$$P^{\mu}\partial_{\mu}f^{i} = -C^{i}f^{i} + D^{i}$$

$$\rho_{00} - \frac{1}{3} \cong \frac{\int_{\tau_0}^{\tau} d\tau' \frac{D_B^0(u,\tau',l) - \bar{D}_B(u,\tau')}{P\cdot u} exp\left[-\int_{\tau'}^{\tau} d\tau'' \frac{C_E(u,\tau'')}{P\cdot u}\right]}{3\int_{\tau_0}^{\tau} d\tau' \frac{D_E(u,\tau')}{P\cdot u} exp\left[-\int_{\tau'}^{\tau} d\tau'' \frac{C_E(u,\tau'')}{P\cdot u}\right]}$$



$$C_B^0 < \bar{C}_B \rightarrow D_B^0 < \bar{D}_B$$



Regeneration will gives $\rho_{00} < 1/3$

05 Summary and outlook

summary

- A possible mechanism about spin alignment.
- Numerical simulation gives opposite sign.
- NLO process gives more contribution.

outlook

- More realistic flow backgrounds change the sign?
- Regeneration gives the right sign.

Thanks for listening!

Zhishun Chen

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